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THE INFLUENCE OF ATMOSPHERIC DYNAMICS ON OZONE AND TEMPERATURE STRUCTURE

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By

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A two-phase sounding program was undertaken at White Sands Missile Range, New Mexico, during the first week of February and June 1973 to measure upper atmosphere temperature, winds, and ozone. In situ and ground-based instrumentation were used. The program was designed to investigate atmospheric transport processes occurring in the lower stratosphere and troposphere. Observations taken in January on the day following the passage of a jet stream over the station showed a large increase (30 percent) in the total

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20. ABSTRACT (cont)

ozone. Also ozone concentration increased as temperature increased at the double tropopause region.

During the second phase of the study, the first week of June, the height of the tropopause moved downward approximately 3 km, from an altitude of 16 km on 1 June to 13 km on 8 June. The variations of ozone in the troposphere and temperature at tropopause altitudes corresponded with associated atmospheric circulation changes, indicating circulation influence at these altitudes

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INTRODUCTION

In recent years, mainly due to interest created by the projected flight of supersonic transports through the stratosphere and the injection of aerosols into the stratosphere, the stratosphere has received a great deal of attention in regard to its composition and to the transport processes which prevail in the region. To better understand transport processes taking place in the stratosphere, near simultaneous measurements of its thermodynamic properties and other parameters which may be useful in describing the atmospheric structure are required. In addition to measurements made at a particular time, prior measurements of various parameters should be taken so that a time history study of the atmosphere structure may be made to evaluate the data accumulated during an intensive measurement program.

The key to a basic understanding of an atmospheric model may involve many different measurements; ultimately, the model will have to be evaluated by experimental data. Therefore, experimental investigations must be performed where instrumentation exists that is capable of monitoring the thermodynamic state and composition of the atmosphere. The facilities of the US Army Atmospheric Sciences Laboratory, White Sands Missile Range (WSMR), New Mexico, are unique because they can be used for making atmospheric measurements with rocket payloads and also for maintaining and operating an extensive array of other meteorological monitoring equipment.

In an attempt to define the dynamic processes involved in the transport of pollutant material in the stratosphere and to determine fine-scale wind structure and turbulence characteristics of the stratosphere, a two-phase measurement program was undertaken at WSMR. Coordinated measurements of wind, temperature, and ozone were made during February and June 1973 with ground-based, balloon-borne, and rocket-borne sensors. In addition, meteorological satellite photos were used to provide an overview of atmospheric conditions which could influence the local weather.

MEASUREMENT PROGRAM (PHASE I)

Wind and temperature structure measurements were made by radiosondes and rocketsondes on 2 February 1973. Radiosondes were released on this day and for several days before to provide atmospheric background.

Fine-scale wind and temperature measurements were made with a Jimsonde. The Jimsondes are 1-m diameter mylar spheres with conical projections. The conical projections prevent vortex shedding so that

the sphere trajectory will more correctly indicate the wind field and the measurement will not be influenced by the dynamics of the flow around the sphere.[1]

The spheres were metalized and were tracked by a radar as they ascended to an altitude of approximately 18 km, at which point they began to float at a constant density surface. Winds are derived from precision radar position data, and temperatures are measured by lightweight sondes affixed to the lower quadrant of the Jimsonde. Temperatures sensed by a bead thermistor are telemetered to a ground receiver where they are recorded on magnetic tape for reduction by a computer. Low altitude meteorological rockets[2] were launched for wind and temperature measurements. The apogee altitude of these rockets was approximately 22 km, which was achieved by utilizing a standard meteorological rocket with a dart stage secured to the booster for added drag. Wind measurements were derived by tracking the descending parachutes with FPS-16 radars. The low altitude meteorological rocket system measured winds from an altitude of 17 to 22 km. The attempts to measure temperature with the Jimsonde and the meteorological rocket were unsuccessful because of poor Jimsonde telemetry systems and broken thermistors in the case of the meteorological rockets.

Total ozone measurements were made by means of a surface-based Dobson spectrophotometer. A vertical ozone profile was derived from a balloon-borne mast ozonesonde.[3] Surface ozone measurements were also made during this period of study.

Table 1 contains a schedule of the measurements by the various sensing techniques and the type of the data derived by these different methods.

DATA ANALYSIS (PHASE I)

An analyis of the photographic data from the meteorological satellite in figure 1 (29 January 1973) shows a jet stream located over Baja, California, extending northeastward, with the most northern position located on the Arizona-New Mexico border. From this point, the jet stream curves south and is positioned just north of WSMR. On subsequent days, the curved trajectory which formed the northern extent of the jet stream flattens and proceeds to move further south each day. Figure 2 shows the weather conditions on 2 February when the jet stream is located several hundred miles to the south of WSMR. These findings were

[1]J. Scoggins, 1965, "Spherical Balloon Wind Sensor Behavior," J Appl Meteorol, 4:139-145

[2]W. L. Webb, 1966, Structure of the Stratosphere and Mesosphere, Academic Press, New York

[3]A. W. Brewer and J. R. Milford, 1960, "The Oxford-Kew Ozonesonde," Proc Roy Soc London, A, 256:470-497

substantiated by wind analysis, using 200 mb pressure charts. With the southerly movement of the jet stream over the site, the upper atmosphere exhibited characteristics associated with the jet, such as an increase in windspeed, ozone concentration, and temperature. On 29 and 30 January the temperature soundings revealed the tropopause to be located at an altitude of 12 km. The jet stream maxima passed over the station on 30 January, as indicated by high windspeeds of 79 m/s at 12.3 km. Once the jet stream maxima passed over the station, the double tropopause became evident from the 31 January sounding, as seen in figure 3. The polar tropopause is located at a height of approximately 8 km and the subtropical tropopause at approximately 16 km. The exact height of the two tropopauses becomes better defined on succeeding days.

Measurements of the total ozone, shown in table 2, indicate a large increase of total ozone over WSMR on 31 January. The total ozone on 26 January is very near the mean for January. The next total ozone measurement, made on 29 January, shows a 6 percent decrease. At this time the jet stream is located north of WSMR. The reading taken on 31 January shows an increase of 31 percent from measurements made 2 days previously. On the 2 succeeding days in February, the ozone begins to show a decrease to a level lower than the average for February. This variation appears to agree fairly well with the progression of the jet stream from a position just north of WSMR to a position, several days later, to the south of WSMR.

As seen in figure 3, the temperature profiles from the radiosonde observation exhibited significant changes in atmospheric structure. On 31 January, a large inversion appears in the temperature sounding from 8 to 10 km which is probably associated with the polar tropopause. The subtropical tropopause appears at approximately 16 km; however, it is not clearly defined because of several small temperature inversions at these altitudes. The sounding on 1 February shows three inversion layers occurring at approximately 5, 10, and 18 km; on 2 February, the inversion layers at 5 and 18 km are reduced in magnitude, and by the time of the 0840 sounding, these latter temperature inversions are no longer present. The inversion layer at approximately 10 km remains, indicating the presence of the polar tropopause, and the subtropical tropopause is easily discernible at 16 km from the 0840 sounding. Table 3 lists the maximum wind and the altitude of occurrence. This wind data as shown in figure 4 indicates that the jet stream was immediately above the station on 30 January. On the following days, the winds decreased as the wind maxima moved further south from the station. The altitude of the jet stream is approximately 12 to 13 km, which is between the heights of the polar and subtropical tropopause. The temperature at the subtropical tropopause height underwent changes during this period, warming slightly from -68°C on 29 January to -64°C on 31 January, and then cooling to -70°C on 2 February.

Jimsonde releases and low altitude meteorological rocket soundings were made on 2 February. The wind data from the Jimsonde have been calculated to have a response wavelength of 50 m. The response of the

descending parachute has been estimated to be approximately the same as the Jimsonde. The temperature data from the Jimsonde and meteorological rocket soundings were intended for use in conjunction with the wind data to derive Richardson numbers to describe the small-scale structure in the lower stratosphere. To date this portion of the program to obtain temperatures has been unsuccessful because, in the case of the meteorological rockets, the bead thermistor broke at expulsion and because the data from the Jimsonde proved to be extremely noisy, making temperature reduction difficult.

The wind data derived from the radar track of the Jimsonde sphere are presented in figure 5. These plots show that there was very little change in the vertical wind field over the 3-hour measurement period. Above 10 km, the wind direction was predominantly from a westerly direction. The maximum wind of 55 m/s occurred at a height of 13 km. The plotted vertical rise rate for the three Jimsondes shows very little variation, with the exception of a slight perturbation at 8 km from the 0930 sounding. The consistency of the data on this day indicates rather stable conditions with very little turbulent structure.

A vertical ozone profile with accompanying temperature structure made on 2 February is shown in figure 6. The two profiles were plotted to show how several of the ozone variations appear to coincide with the temperature variation. At an altitude of approximately 10 km (the height of the polar tropopause), a temperature inversion is shown, and, at nearly the same altitude, the ozone showed a slight increase in concentration. Above the polar tropopause, temperatures decreased up to the subtropical tropopause at an altitude of 16 km. The ozone data show an increase with height from 16 to 19 km, with a small ozone peak occurring above the subtropical tropopause. These two increases appear to have good correlation with the two tropopause regions in the atmosphere.

The surface ozone measurements (table 4) made during this period show maximum ozone near the surface on 31 January and a decrease thereafter. These measurements correlate very well with the presence of the jet stream in the vicinity.

MEASUREMENTS PROGRAM (PHASE II)

The second study on atmospheric dynamics was made during the first week of June 1973 and extended throughout the week instead of concentrating on several days as was done in phase I. Table 5 gives the schedule of observation and the sensors deployed during that period. Jimsondes and low altitude meteorological rockets were not deployed during the second phase of study; however, Arcas rockets were launched to determine the ozone concentration in the stratosphere.

Synoptic changes during phase II of the study over WSMR are shown by constant pressure charts (200 mb) in figures 7 through 10. A weak trough was present near the West Coast (figure 7) on 1 June. This

trough moved quickly over WSMR during the observation period as is seen in figures 8 and 9. On 1 June, high winds (90 knots ≈ 45 m/s) were observed (shaded area) as the tropical jet stream and the polar jet stream joined together as indicated by a double tropopause. This situation did not remain for long as is indicated by the wind profiles observed on 4 and 6 June, and on 8 June the polar jet moved far north of WSMR (figure 10).

The temperature profiles from the radiosonde observations made during the week are shown in figure 11. Winds are plotted in figure 12. There is a significant change in the tropopause height during the course of 1 week in changing from 16.5 km on 1 June to 13.5 km on 8 June. Wind profiles show a maximum near 12.5 km. A change in the direction of the wind in the troposphere was observed on 8 June (easterly) as compared to the other three profiles (westerly); however, there was no significant change at the lower stratospheric levels (all easterlies) during the week.

Measurements of the total ozone shown in table 6 indicate no change during the week of observations except a 12 percent decrease which occurred after 31 May. Ozone profiles obtained from the electrochemical ozonesonde (mast) releases are shown in figure 13. Ozone concentration in the troposphere shows an increase on 6 and 8 June as compared to 1 and 4 June, although the ozone peak does change on these days. The increase in ozone concentration at tropospheric levels correlates positively with the downward movement of tropopause. Two rocket observations made on 6 and 8 June by a rocket ozonesonde[4] are shown in figure 14 and exhibit significant variability in ozone concentration at the stratospheric levels. Increase of ozone concentration at stratospheric levels shown by the 8 June profile is consistent with the increase observed by the Dobson spectrophotometer on that day.

The two rocket observations of ozone were made on different times of the day--one in the early morning hours and the other near sunset time. The variability is in agreement with the photochemical theory and seems to be real.

ANALYSIS OF MESOSCALE VARIATIONS

The main emphasis of this report has been in relating large-scale synoptic type motions to their effect upon ozone distribution and meteorological parameters. Since radiosonde data collected during the period (31 January to 2 February 1973) were available, the mesoscale variations could be analyzed. Radiosonde data were obtained from two locations: a

[4]J. S. Randhawa, 1967, "Ozonesonde for Rocket Flight," Nature, 213:53

station located near the Post area, and Holloman Air Force Base a distance of 64 km. The data were analyzed to determine the gradient Richardson number by use of the following equation

$$Ri = \frac{g}{T}\left[\frac{\partial T}{\partial z} + \Gamma\right]\left(\frac{\partial u}{\partial z}\right)^{-2} \tag{1}$$

where g is the acceleration of gravity, T is the atmospheric temperature ($^{\circ}$K), Γ is the adiabatic lapse rate (9.9°K m^{-1}), z is the vertical coordinate which specifies the buoyancy term, and u is the horizontal wind velocity such that $\partial u/\partial z$ specifies the vertical wind shear. The critical value of Ri, equation (1), is believed to be about 0.25. When Ri is less than 0.25, turbulence is created.

In the general case, the combination of buoyancy and shear must be considered when determining where turbulence should be generated. Sloping baroclinic layers, even though stable in the sense that the temperature lapse rate is positive, often contain large wind shears which lead to a Richardson number below the critical value and hence turbulence. On the basis of the availability of eddy kinetic energy, turbulence is likely to occur under the following conditions:

1. Near the jet stream where shear is large and buoyancy stability is not too large in the negative sense.

2. In any region or layer where buoyancy is small and nominal or greater shear is present (the magnitude of the critical shear required depends upon the degree of stability).

3. In sloping baroclinic layers where wind shear is large enough to overcome the negative (stabilizing) effects of stability (note the fact that shear is squared, whereas stability is to the first power).

4. Near the ground where wind shear is large due to frictional effects, and buoyancy is small due to mixing.

The critical value of the Richardson number is based upon the concept of a local derivative. When derivatives are evaluated over a layer such as 2000 ft (0.61 km) as was done in the computations, the result is an average Richardson number for the layer. The relationship between Richardson numbers over layers of various thicknesses is not well known; but because of the accuracies and resolution of the data, it is often assumed that small Richardson numbers over rather thick layers imply a small local Richardson number. Thus when the Richardson number computed over a layer of finite thickness becomes small (this is a relative thing since the magnitude is highly a function of the layer thickness), it is assumed that the local Richardson number will be small at some point within the layer and hence conditions favorable for the production of turbulence. The critical Richardson number corresponding to a layer of finite thickness is in general unknown, but it is known that it should

be greater than 0.25, and further that turbulence is more likely in regions where the Richardson number is small relative to other regions. From a profile of the Richardson number, it is possible to isolate altitude bands where turbulence is more likely to occur than in other altitude bands; and from profiles of the buoyancy and mechanical production terms, it is possible to infer which of these is likely to be responsible for the turbulence. As is clearly evident from the analysis of the soundings, there are cases where small Richardson numbers result from small buoyancy, in others from large shear, and in still others from combination of the two. It would not be wise to attempt to infer regions of small Richardson numbers from either the temperature or wind profile considered alone.

The gradient Richardson number was computed for each rawinsonde profile at intervals of 1000 ft (0.30 km) and over a depth of 2000 ft (0.61 km). Thus there was an overlap in the layers. Wind and temperature data were obtained from each rawinsonde sounding. The convective and mechanical production terms were calculated separately, then divided to obtain the Richardson number. Profiles of all three parameters were computed for each sounding. The Richardson number represents the ratio of convective (buoyancy) to mechanical (wind shear) production of turbulence.

The fact that large changes in the Richardson number may occur over relatively short horizontal distances is illustrated by the soundings at 0200 local time on 31 January 1973 from WSMR and Holloman Air Force Base, as shown in figures 15 and 16. In the altitude range between about 20,000 ft (6.1 km) and 26,000 ft (7.9 km) at WSMR, the Richardson numbers were quite large while those at Holloman were quite small. At altitudes above about 26,000 ft (7.9 km), the reverse condition occurred. Large differences such as these can result from the influence of mountain waves or some other local influence which does not extend over large horizontal distances. This case illustrates why such large changes in turbulence are often observed over short distances. From the shear and buoyancy profiles for the two soundings, it is clear that wind shear is primarily responsible for the large differences in the Richardson number profiles. Here note that in the altitude band between 20,000 ft (6.1 km) and 26,000 ft (7.9 km) where the Richardson number is smaller at Holloman than at WSMR, the buoyancy was even a little higher at Holloman than at WSMR, but it was a nominal increase in shear at Holloman that caused the Richardson number to be low. This low number is due primarily to the fact that shear is squared in the equation and therefore has a large influence.

Another phenomenon from the Richardson number profiles on 31 January relative to changes with time can be observed. The small Richardson numbers observed at WSMR from 26,000 ft (7.9 km) to 50,000 ft (15.2 km) at 0200 local time increased by a factor of about five by 0900 local time (figure 17). There were some changes in buoyancy observed, but the primary reason for this change in the Richardson number was significant decrease in the shear (figures 18 and 19). There is no question that

large temporal and spatial variations which occur on a scale of only a few miles are of great importance when considered in relation to turbulence. The Richardson number profiles seem to indicate a higher probability for the occurrence of turbulence on 31 January and 2 February than on 1 February. However, there are layers within which the Richardson number is quite small on all days, indicating that turbulence might have been present in these layers, but the layers are not as deep on 1 February as they are on 31 January and 2 February (figures 15, 18, and 19).

SUMMARY AND CONCLUSIONS

The two studies, one made in a turbulent atmosphere during winter and the other made under relatively stable conditions, have indicated the dynamic nature of the atmosphere with changes in the thermodynamic structure as well as in the ozone. The presence of a jet stream over the station during the winter did produce large changes in total ozone due to the interchange of constituents between stratosphere and troposphere. With the increase in temperature, an increase in ozone concentration was observed near the tropopause region. The turbulence associated with the jet stream caused departures in the ozone concentrate from the concentrate of the seasonal mean, since photochemical processes at these levels proved to be slow in comparison to rapid increases and decreases of ozone noted in this study.

The summer study made under relatively stable atmospheric conditions did show some influx of ozone from stratosphere to troposphere as the tropopause moved downward.

The bulk of in situ measurements in this two-phase study was confined to the troposphere and lower stratosphere. To fully define the atmospheric processes involved, measurements of temperature, winds, and ozone through the entire stratosphere would be useful.

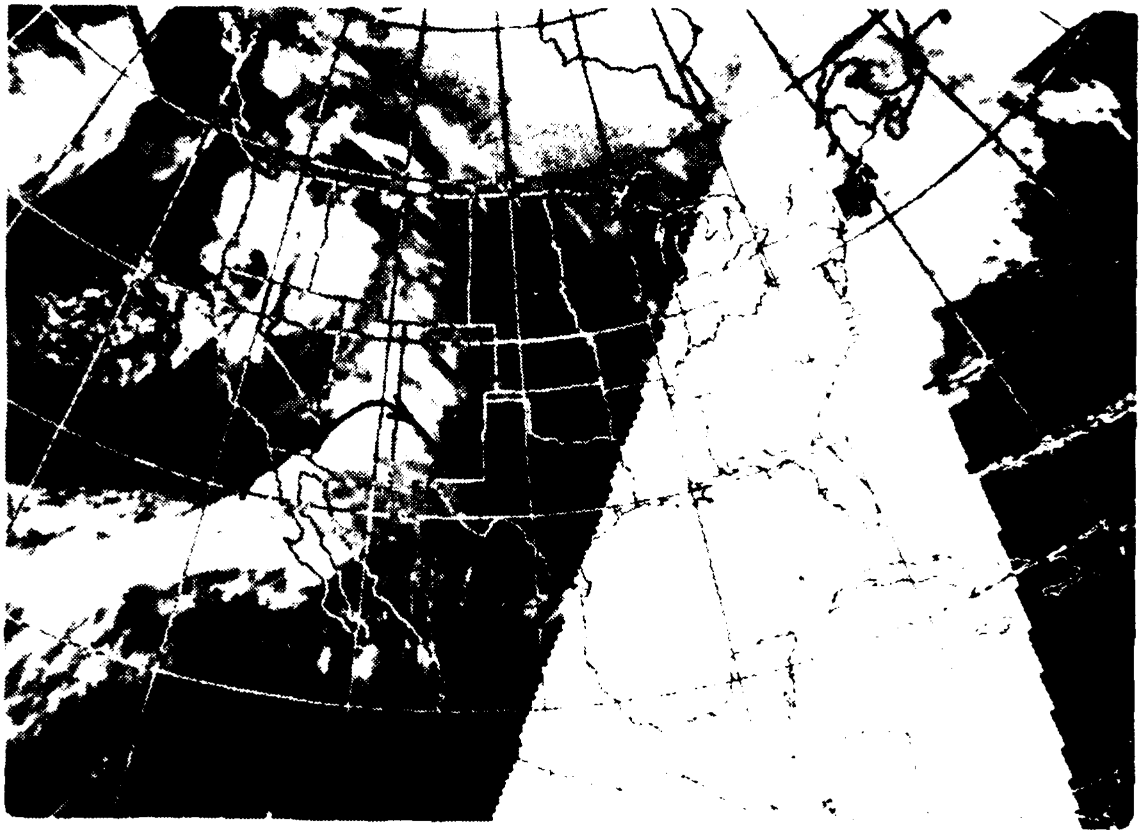

Figure 1. Meteorological satellite photo, 29 January 1973.

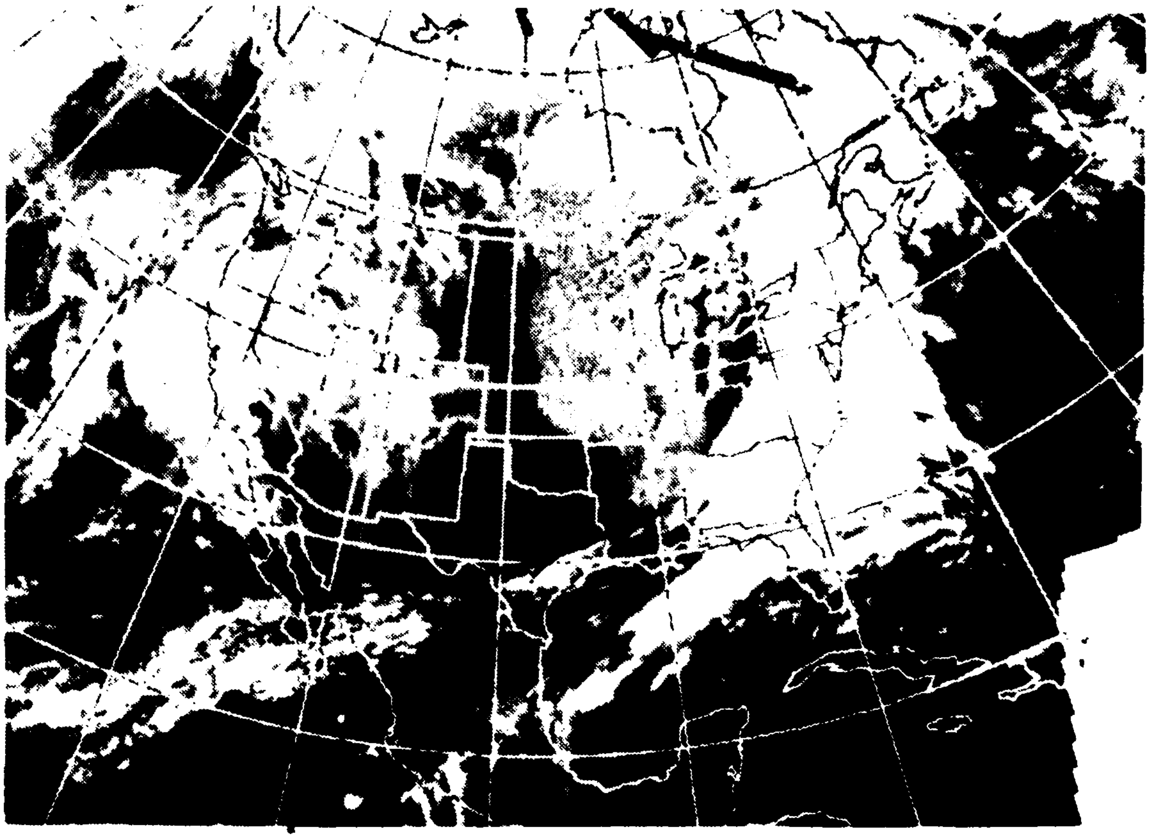

Figure 2. Meteorological satellite photo, 2 February 1973.

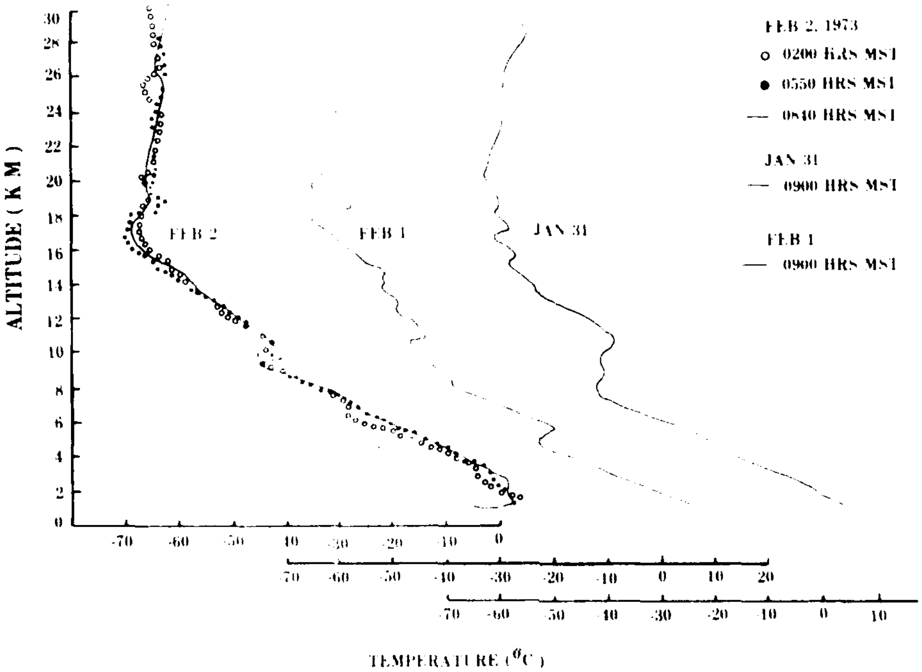

Figure 3. Radiosonde temperature profiles for 31 January and 1 and 2 February 1973.

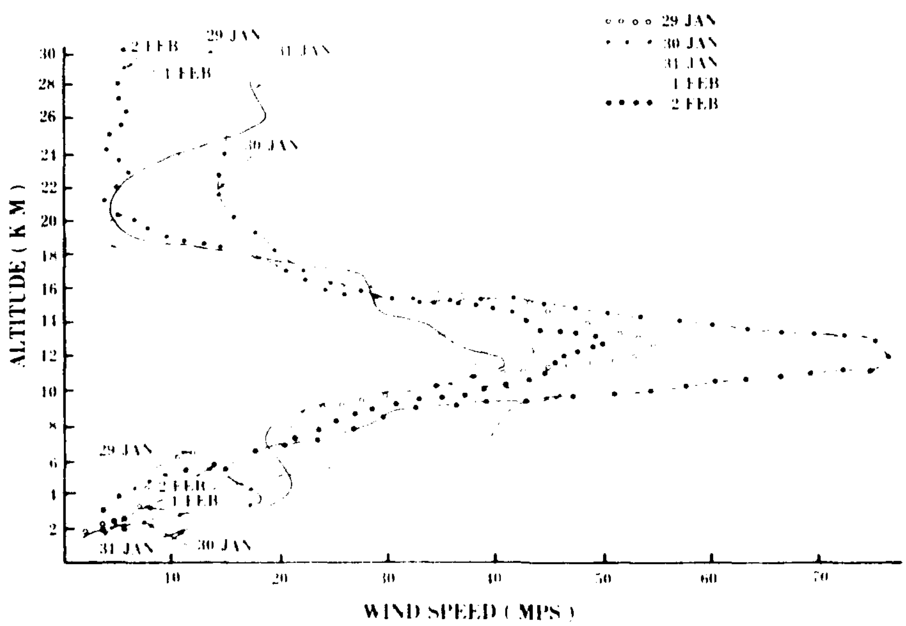

Figure 4. Wind profiles for 29, 30, 31 January, and 1 and 2 February 1973.

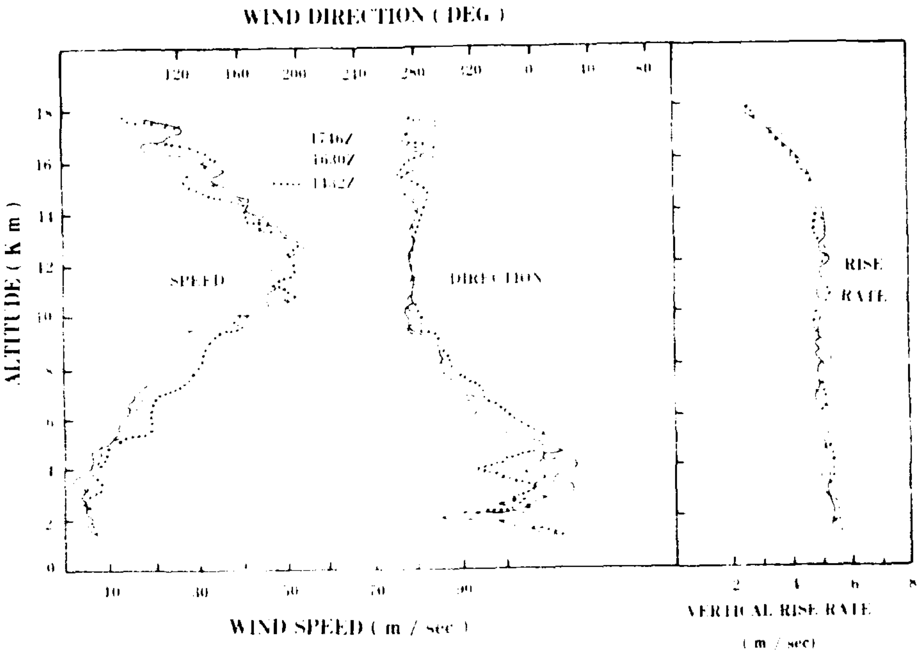

Figure 5. Jimsonde wind profiles, 2 February 1973.

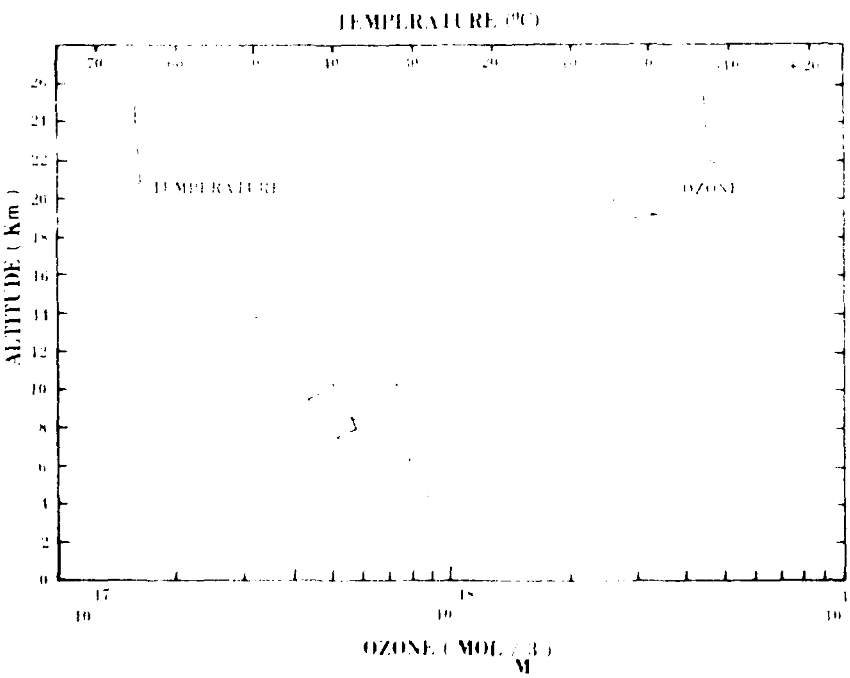

Figure 6. Ozone and temperature profiles for 2 February 1973.

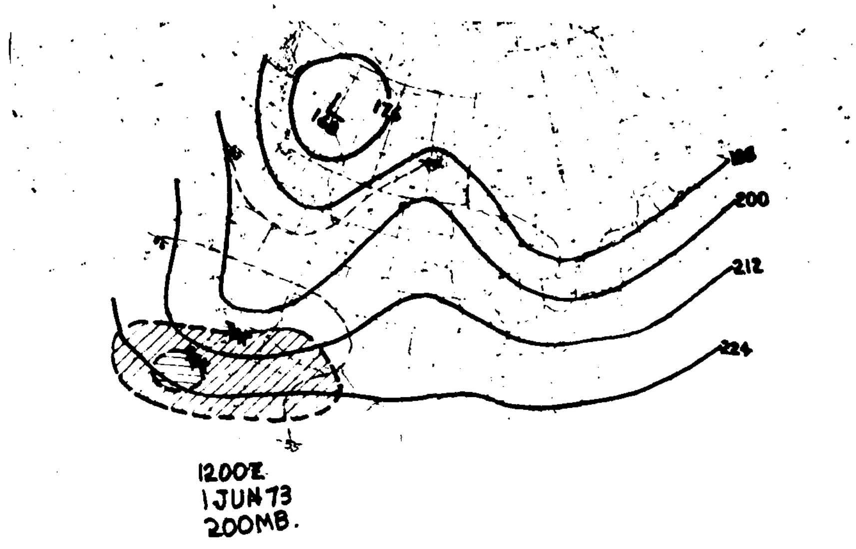

Figure 7. Synoptic chart (200 millibar) on 1 June 1973 for North America.

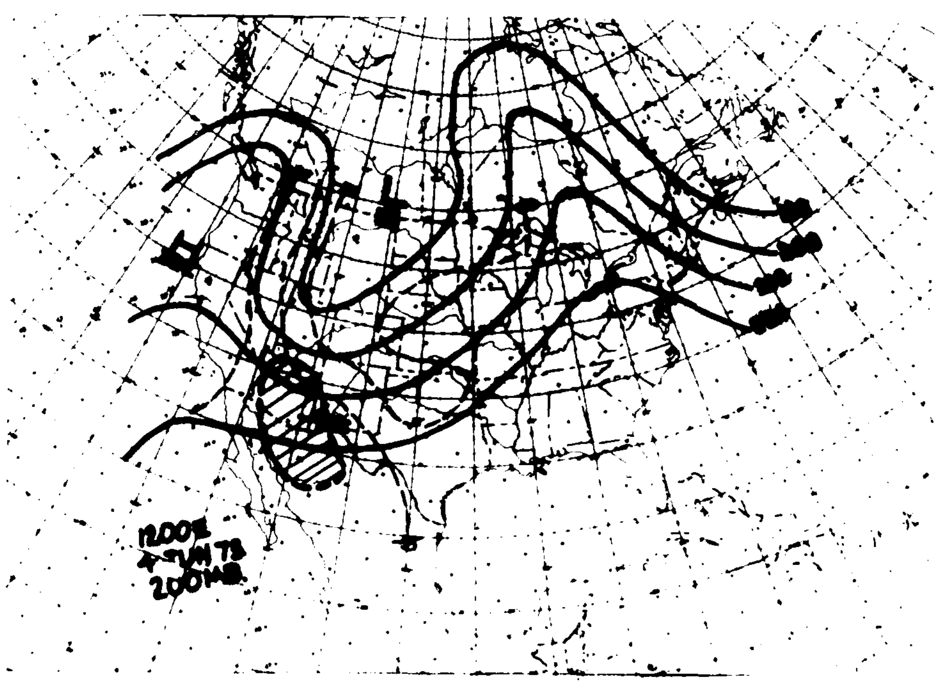

Figure 8. Synoptic chart (200 millibar) on 4 June 1973 for North America.

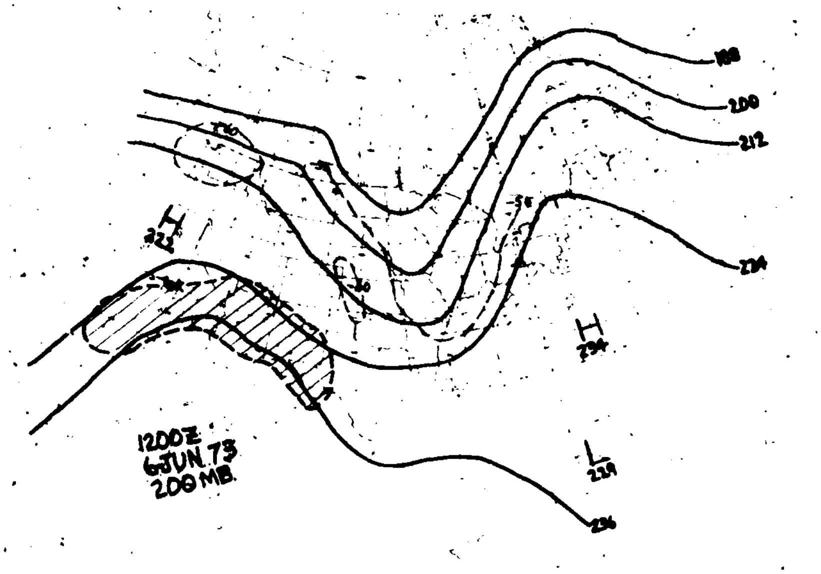

Figure 9. Synoptic chart (200 millibar) on 6 June 1973 for North America.

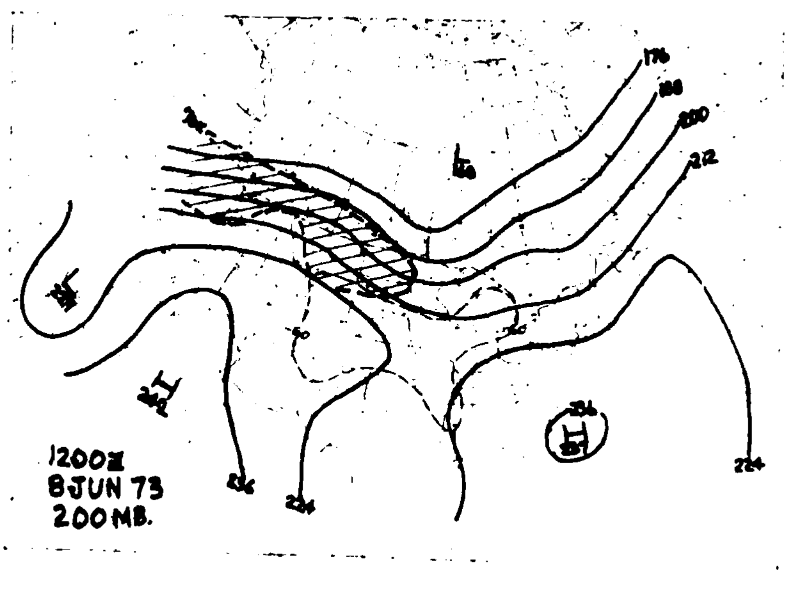

Figure 10. Synoptic chart (200 millibar) on 8 June 1973 for North America.

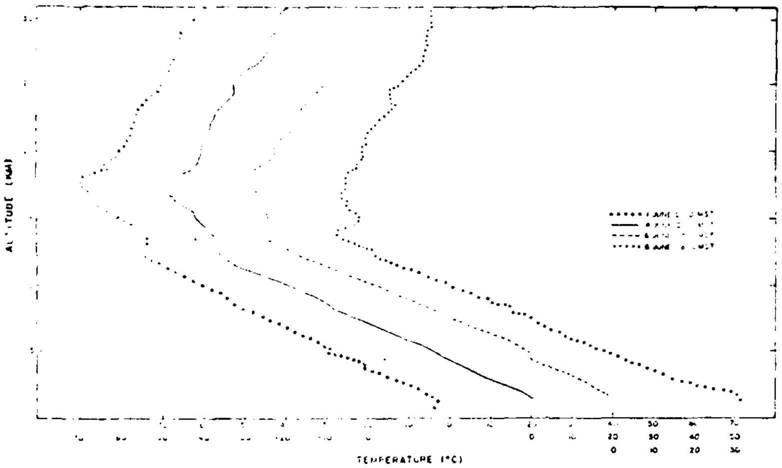

Figure 11. Radiosonde temperature profiles for 1, 4, 6, and 8 June 1973.

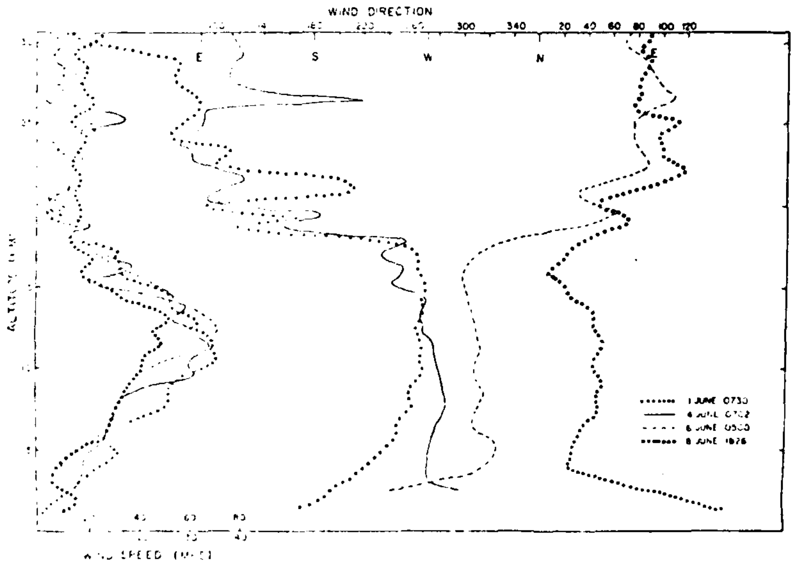

Figure 12. Wind profiles for 1, 4, 6, and 8 June 1973.

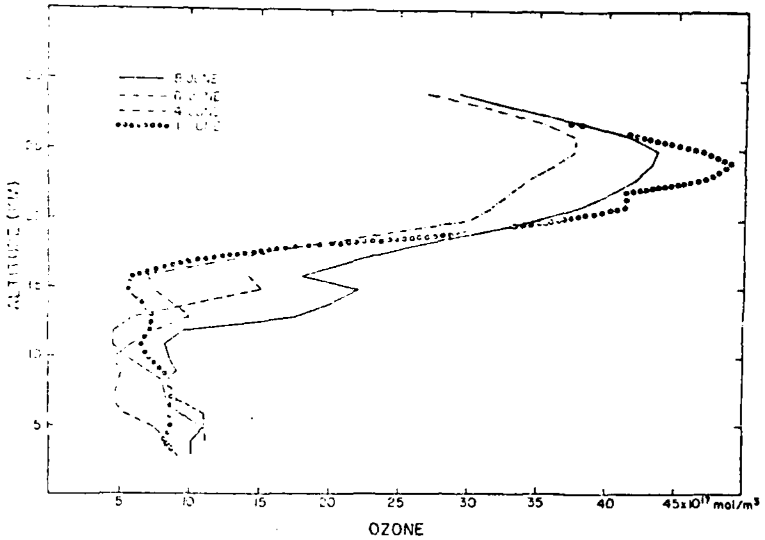

Figure 13. Ozone concentration profiles for 1, 4, 6, and 8 June 1973 obtained from electrochemical ozonesonde.

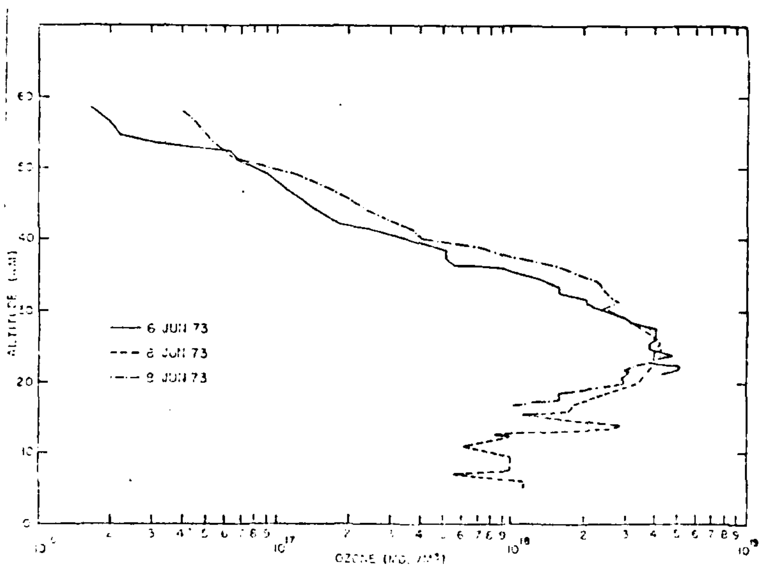

Figure 14. Ozone concentration profiles for 6 and 8 June 1973, obtained from rocket ozonesonde; 8 June 1973 data from electrochemical sonde is also shown on this figure.

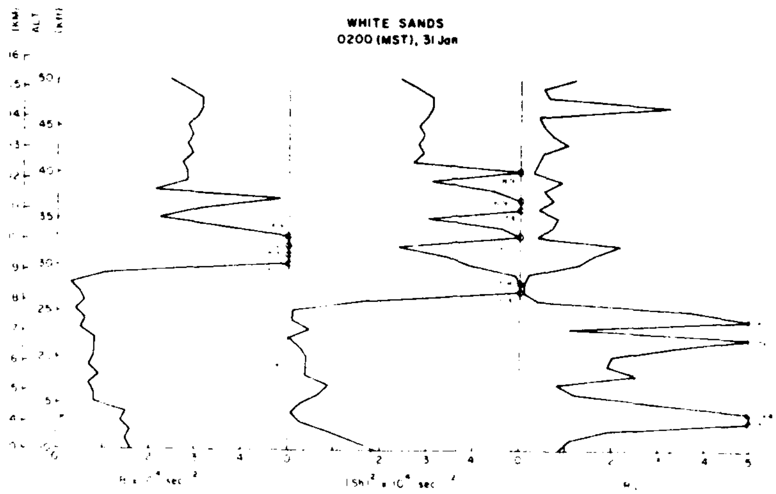

Figure 15. Buoyancy, shear, and Richardson numbers, White Sands, 0200 MST, 31 January 1973.

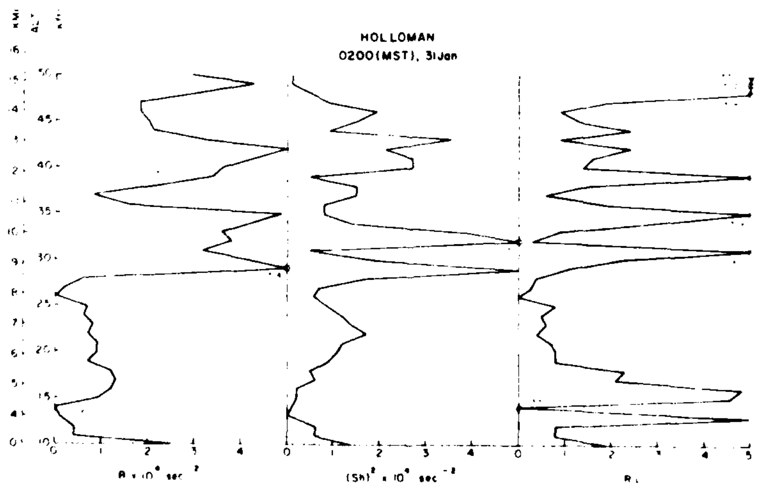

Figure 16. Buoyancy, shear, and Richardson numbers, Holloman AFB, 0200 MST, 31 January 1973.

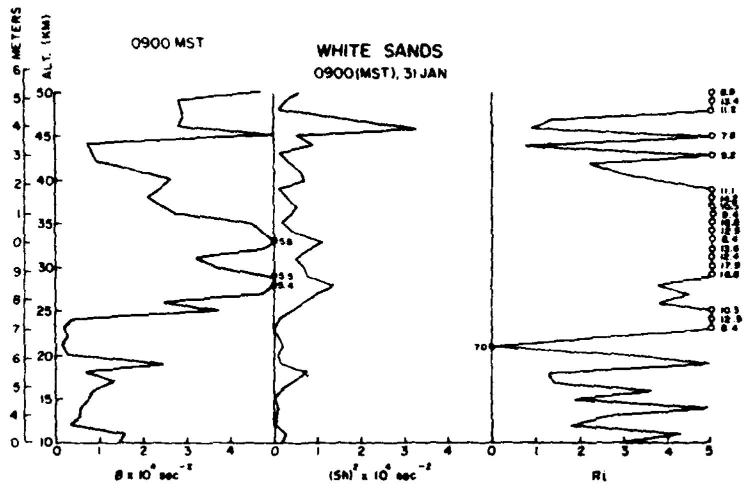

Figure 17. Buoyancy, shear, and Richardson numbers, White Sands, 0900 MST, 31 January 1973.

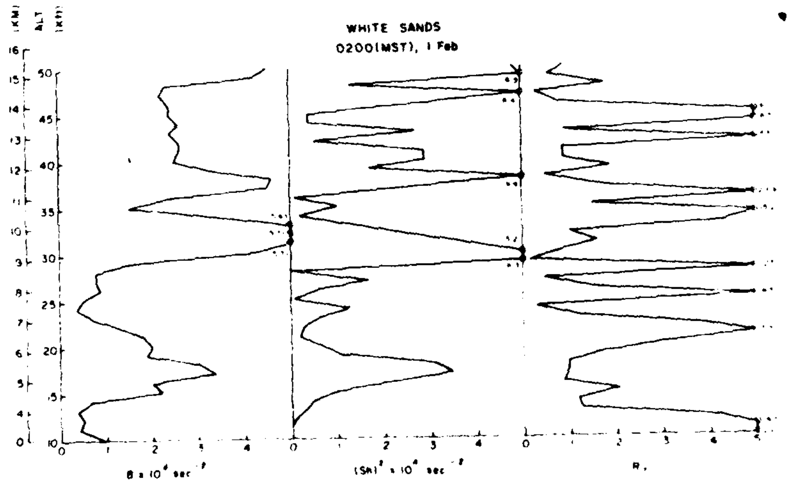

Figure 18. Buoyancy, shear, and Richardson numbers, White Sands, 0200 MST, 1 February 1973.

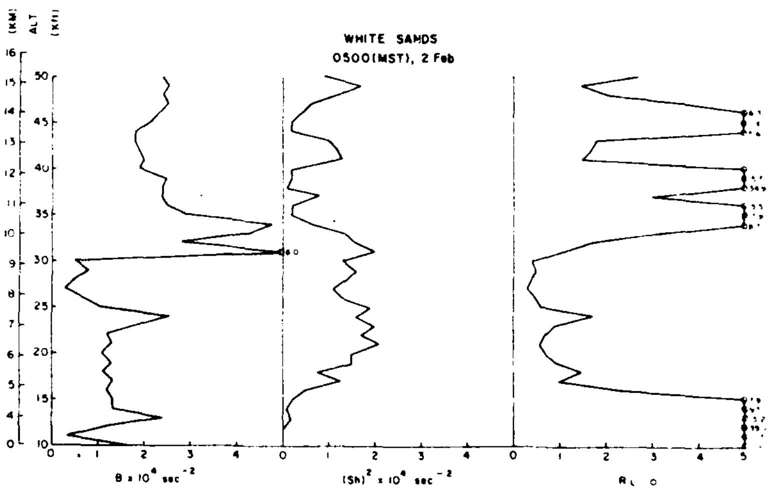

Figure 19. Buoyancy, shear, and Richardson numbers, White Sands, 0550 MST, 2 February 1973.

TABLE 1. MEASUREMENTS BY VARIOUS SENSING TECHNIQUES AND DATA DERIVED FROM MEASUREMENTS

Sensor	Date (1973)	Time (MST)	Data
Meteorological Satellite Photo	29 Jan	0848	Jet stream north of WSMR
	2 Feb	0548	Jet stream south of WSMR
Radiosonde	29-30 Jan	0200	Wind and temperature, surface to 30 km
	31 Jan-1 Feb	0900	
	2 Feb	0200	
	2 Feb	0550	
	2 Feb	0840	
Jimsonde	2 Feb	0732	Wind data, surface to 18 km, no temperature due to noisy telemetry
	2 Feb	0930	
	2 Feb	1046	
Meteorological Rockets	2 Feb	0847	Wind data, 17 to 22 km, no temperature due to broken thermistors
Mast Ozonesonde	2 Feb	1300	Ozone and temperature from surface to 26 km
Electrochemical Ozonesonde	29 Jan-2 Feb	continuous	Surface ozone
Dobson Spectrophotometer	26 Jan-2 Feb	1000	Total ozone over WSMR

TABLE 2. TOTAL OZONE MEASUREMENTS

Date (1973)	Time (MST)	Ozone (atm cm)	Percent Variation From Previous Reading
26 Jan	1000	0.315	0
29 Jan	1000	0.297	-6
31 Jan	1013	0.398	+31
1 Feb	1002	0.324	-17
2 Feb	1000	0.282	-13

January mean 0.303

February mean 0.314

Seasonal max (May) 0.339

Seasonal min (Nov) 0.283

Seasonal variation 18%

TABLE 3. JET STREAM WIND VELOCITIES AND ALTITUDES

	29 Jan 73	30 Jan 73	31 Jan 73	1 Feb 73	2 Feb 73
Windspeed (m/s)	55	79	42	43	51
Direction (deg)	280	270	267	276	280
Altitude (km)	12.3	11.8	12.0	12.5	13.0

TABLE 4. SURFACE OZONE MEASUREMENTS

Date (1973)	Max (pphm)	Min (pphm)
29 Jan	3.0	0.2
30 Jan	3.7	0.8
31 Jan	4.7	3.6
1 Feb	4.3	1.8
2 Feb	4.1	0.1

TABLE 5. SCHEDULE OF OBSERVATION AND SENSORS DEPLOYED

Sensor	Date (1973)	Time (MST)	Data
Radiosonde	1 Jun	0100	Wind and temperature data sfc to 30 km
	4 Jun	0702	
	6 Jun	0500	
	8 Jun	1826	
Dobson Spectrophotometer	31 May	1412	Total ozone over WSMR
	4 Jun	(Averaged over four obs)	
	5 Jun	"	"
	6 Jun	"	"
	7 Jun	"	"
	8 Jun	"	"
Mast Ozonesonde	1 Jun	0930	Ozone profile from sfc to 30 km
	4 Jun	0850	
	6 Jun	0900	
	8 Jun	0900	
Rocket Ozonesonde	6 Jun	0537	Ozone profile from 55 to 15 km
	8 Jun	1851	

TABLE 6. TOTAL OZONE MEASUREMENTS

Date (1973)	Ozone (atm cm)	Percent Variation From Previous Reading
31 May	0.340	0
4 Jun	0.298	-12
5 Jun	0.321	+7
6 Jun	0.316	-1.6
7 Jun	0.327	+3.5
8 Jun	0.328	0

June mean 0.311

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